Kappendecke 2.0

Structural form-finding and digital fabrication of a 3D-printed self-supporting vaulted ceiling.

1 Abstract
The aim of this master thesis is to rethink the historical ceiling construction of the Kappendecke in a contemporary way. By using structural design tools and digital fabrication methods a ceiling system that can be built without formwork, based on several requirements related to structure, construction and architectural design, shall be developed. The first part of this thesis deals with the research of historical ceiling systems and the exploration of novel formwork-free, 3D printed structures with a focus on structural design and digital fabrication (Figures 1.1, 1.2). The gain in knowledge from the first part forms the basis of the second part, whereby a design-study-cycle is approached to reach the optimal result. Each cycle starts with a form-finding to generate a first geometry (Figures 2.1-2.8). This geometry is then simulated and analysed in terms of the structural system, the fabrication process, the architectural concept and the visual appearance. If this analysis proves the form-found structure, this geometry is then adapted for printing and fabricated by a seven-axis robot (Figures 3.1-3.3). The knowledge generated from this process is then used as the base for further design cycles. To prove the concept of this work, several prototypes based on different geometrical solutions are fabricated and evaluated within this master thesis (Figures 4.1-4.4). In combination with a technical ceiling construction, these final prototypes are implemented into Architecture in the last step of this work to demonstrate the architectural applicability (Figures 5.1-6.2).

2 Research objective
Based on the state of the art research (Figures 1.1, 1.2), the aim of this master thesis is to redesign the historical Kappendecke by using structural form-finding tools and digital fabrication methods. Out of this objective, the following research question can be concluded: „Can a traditional Kappendecke, redesigned with structural from-finding tools, be additive manufactured without any support structure?"

3 Method
To validate this research question, the following design approach is going to be used in this master thesis. First, based on the state-of-the-art research, the global constraints and the architectural concept, an initial geometry is generated either by the CEM tool (Figures 2.1, 2.2) or via a geometrical method (Figures 2.3-2.8) depending on the type of structure and the boundary conditions. Based on this geometry a toolpath is generated in the second step (Figures 2.4, 2.8). The following step evaluates this printpath based on the structural system, the architectural concept, and the global constraints. Based on this evaluation, either the form-finding starts again, or if the evaluation proves the form-found geometry, the structure is prepared for fabrication, simulated with a virtual robot to validate the fabrication setup and the robot movements, and is ultimately 3D printed as a prototype in the following three steps (Figures 3.1-3.3). This prototype is then evaluated in the last step and therefore forms the basis for further design cycles. Until the research question can be answered this approach is continued.

4 Conclusion
This master thesis researches historical references (Figures 1.1, 1.2) on form-work-free erected structures and current research on supportless concrete printing as a foundation for the further work. Based on this state of the art research, in the next step, a method is developed to print five design studies in the subsequent steps without using any form-work (Figures 2.1-4.4). The design studies one to four could be printed either with two or even with only one printlayer. Design study five, unfortunately, could not be printed either due to a problem with the fabrication setup or due to wrongly tilted toolpath planes. At the end, an architectural concept is developed to implement the gained knowledge into architecture (Figures 5.1-6.2).

Figure 0.1: Final prototype of design study 4

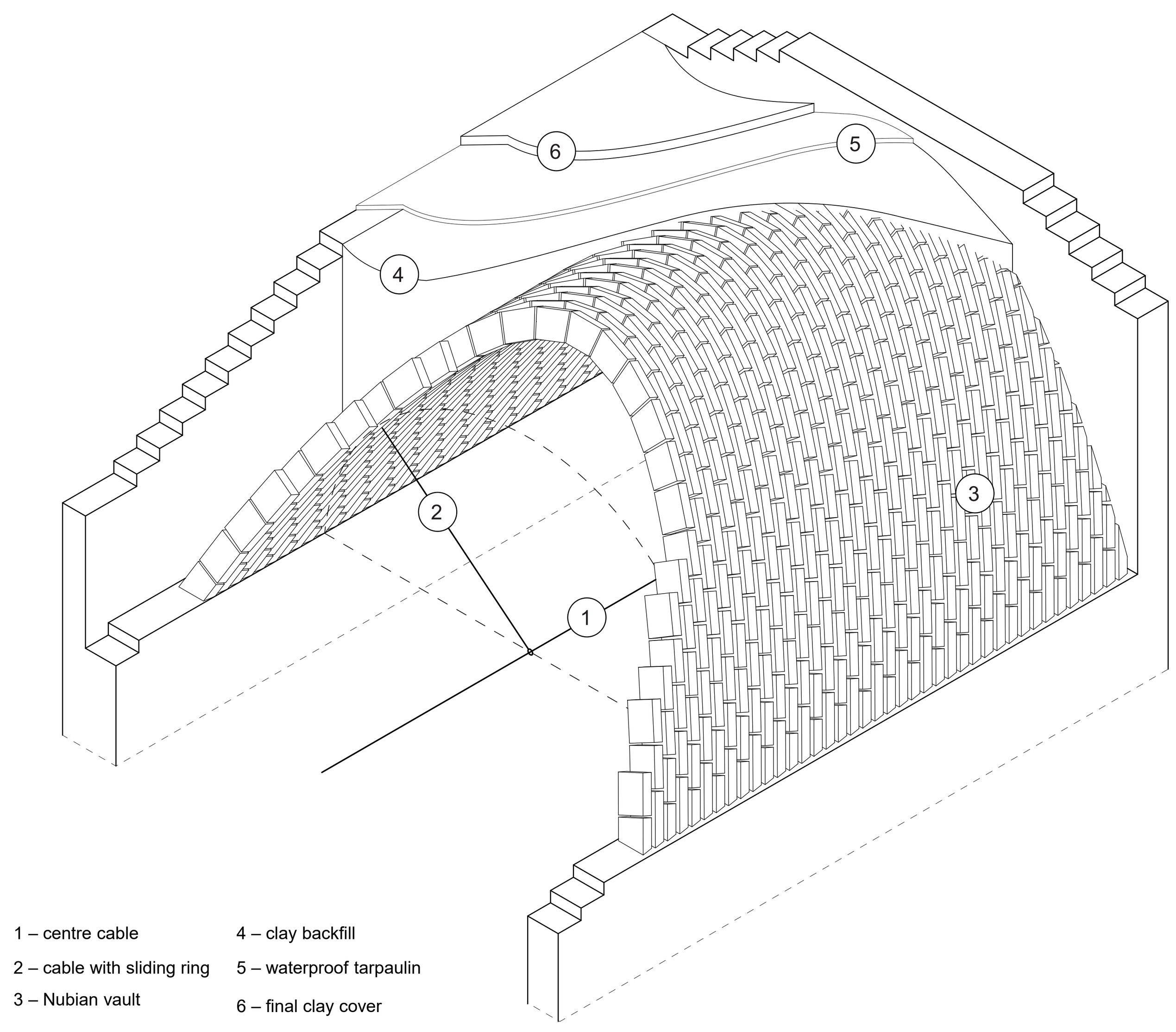

Figure 1.1: Historical reference - Nubian vault

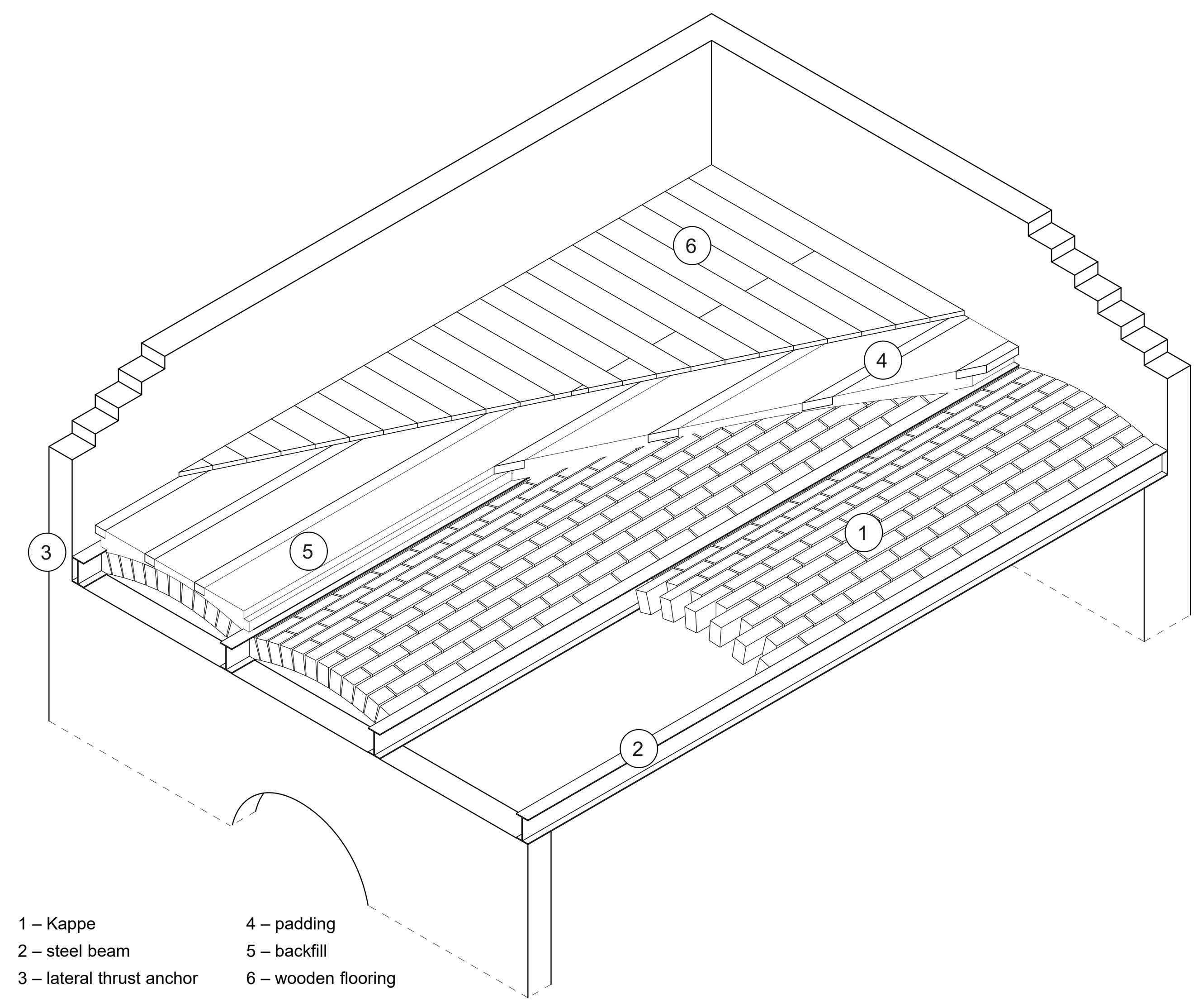

Figure 1.2: Historical reference - Traditional Kappendecke

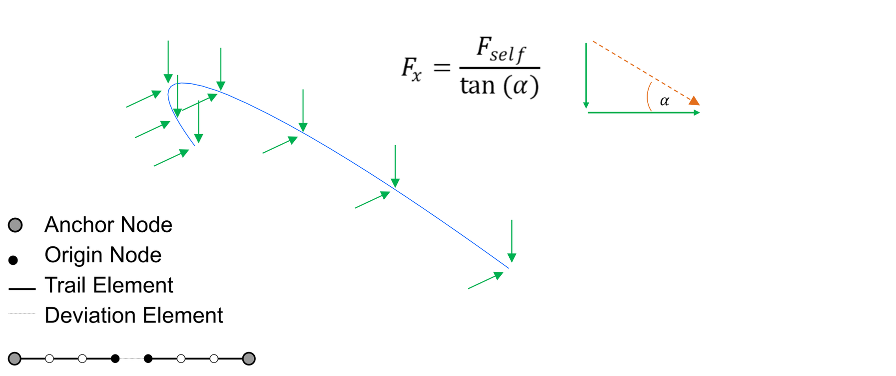

Figure 2.1: First step of structural form-finding of the main part by using combinatorial equilibrium modeling (CEM)

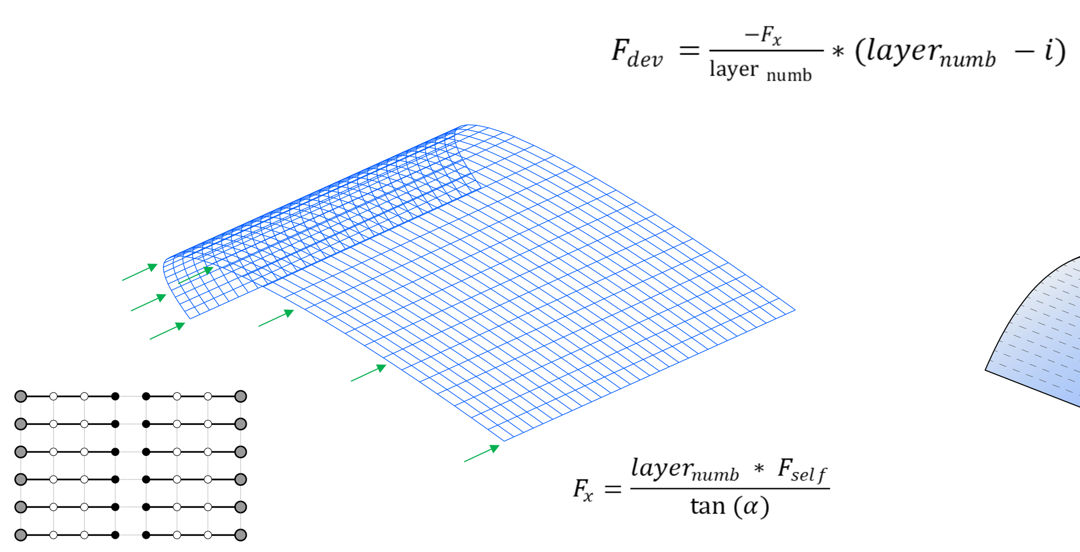

Figure 2.2: Final step of structural form-finding of the main part by CEM

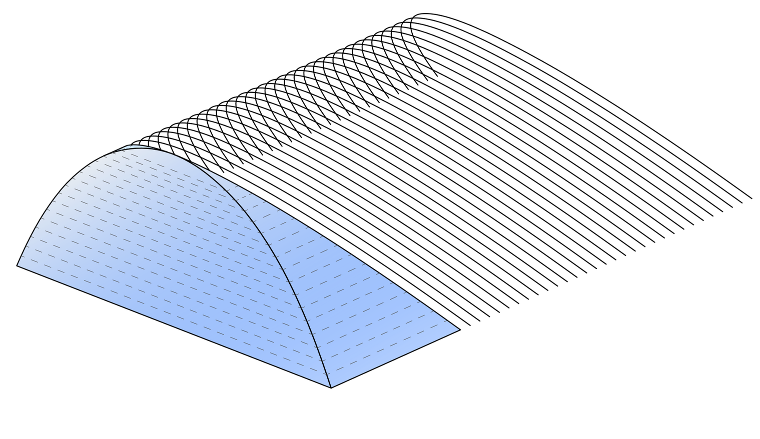

Figure 2.3: Design study 1 - Linear closing geometry

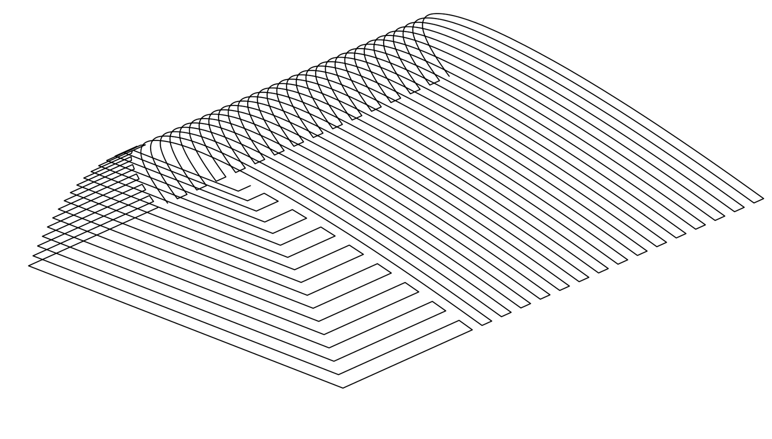

Figure 2.4: Design study 1 - Final single-layered printpath

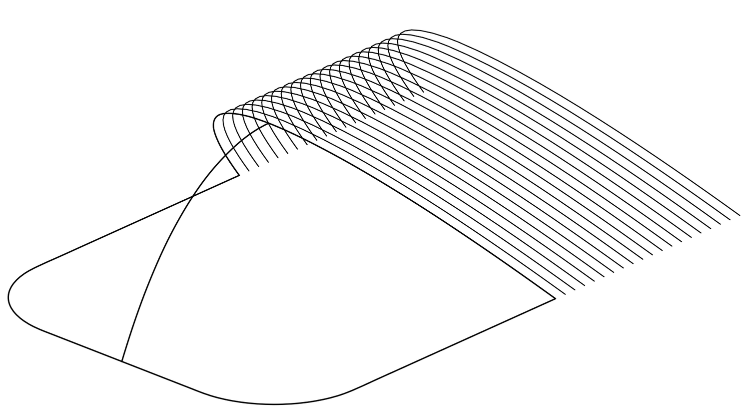

Figure 2.5: Design study 4 - Boundary curves

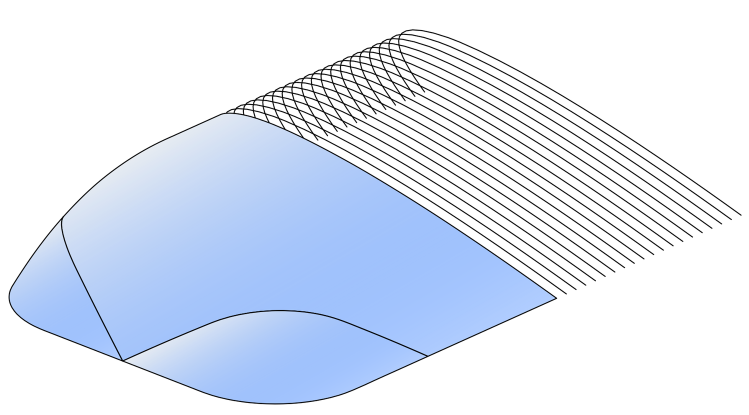

Figure 2.6: Design study 4 - Closing surface

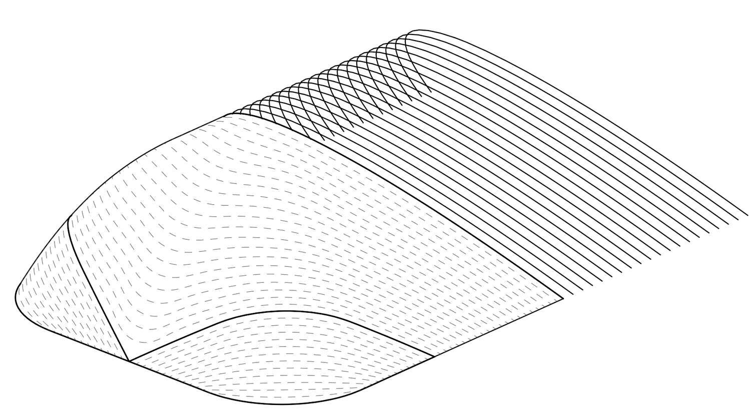

Figure 2.7: Design study 4 - Printpath interpolation

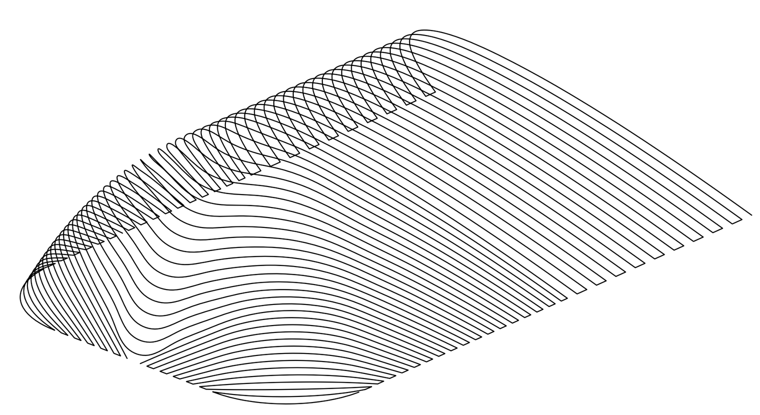

Figure 2.8: Design study 4 - Final single-layered printpath

Figure 3.1: Robotic fabrication setup

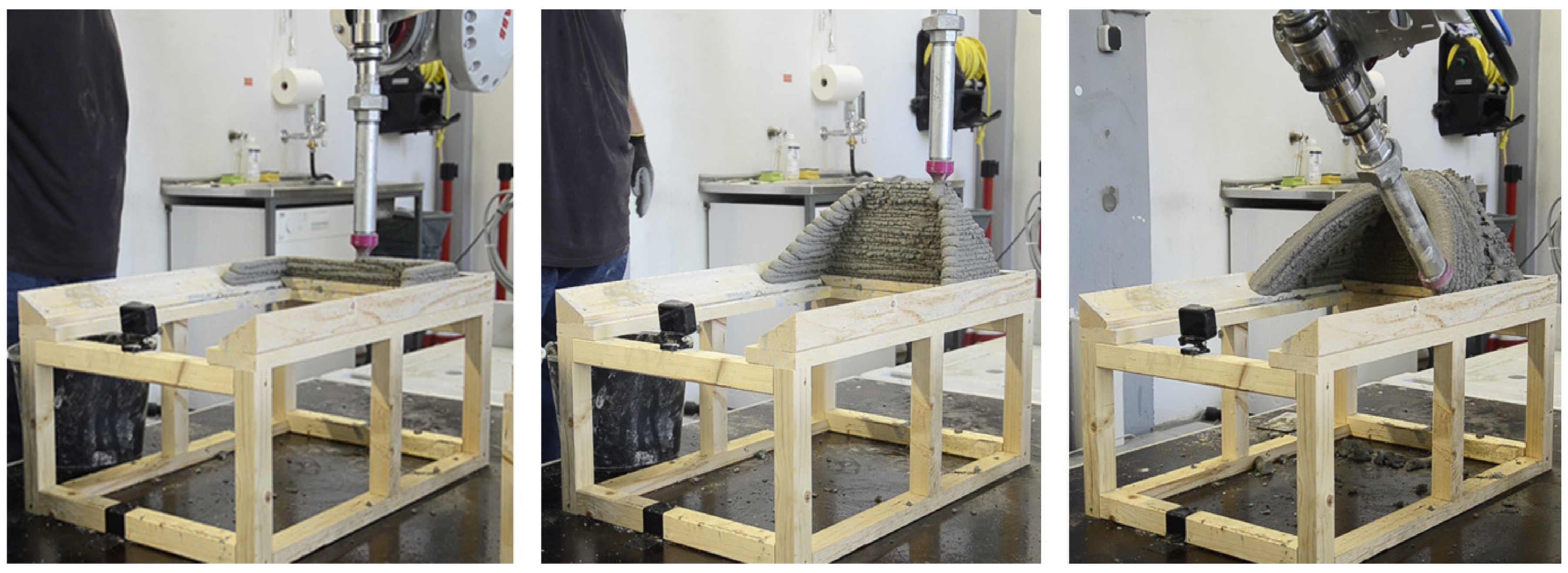

Figure 3.2: Fabrication of design study 1

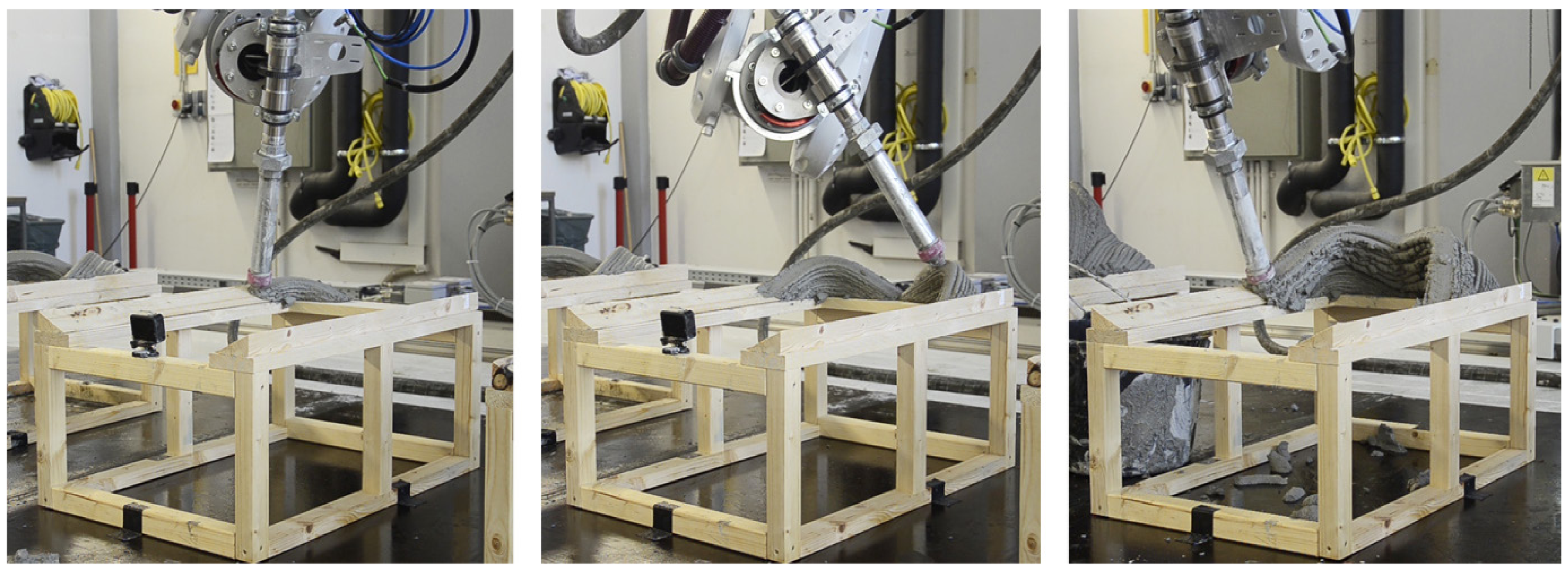

Figure 3.3: Fabrication of design study 4

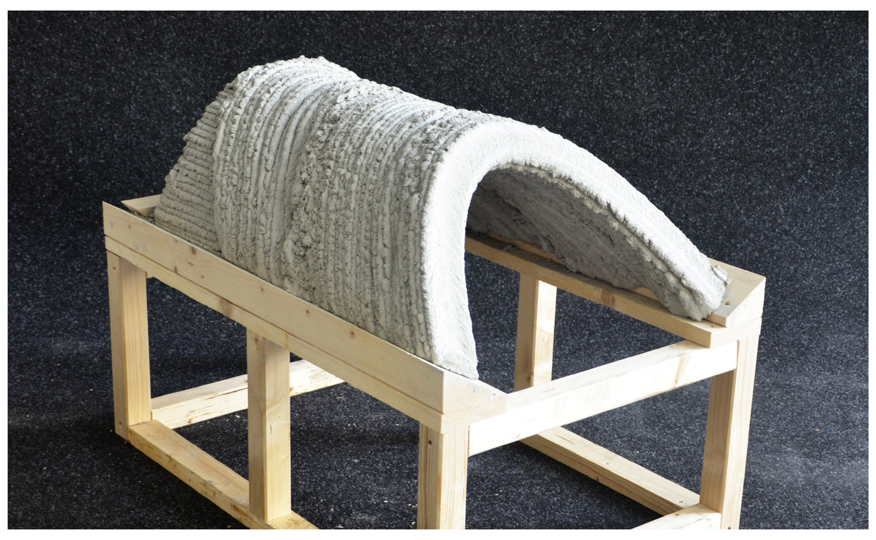

Figure 4.1: Final prototype of design study 1 - Front side

Figure 4.2: Final prototype of design study 1 - Back side

Figure 4.3: Final prototype of design study 4 - Front side

Figure 4.4: Final prototype of design study 4 - Back side

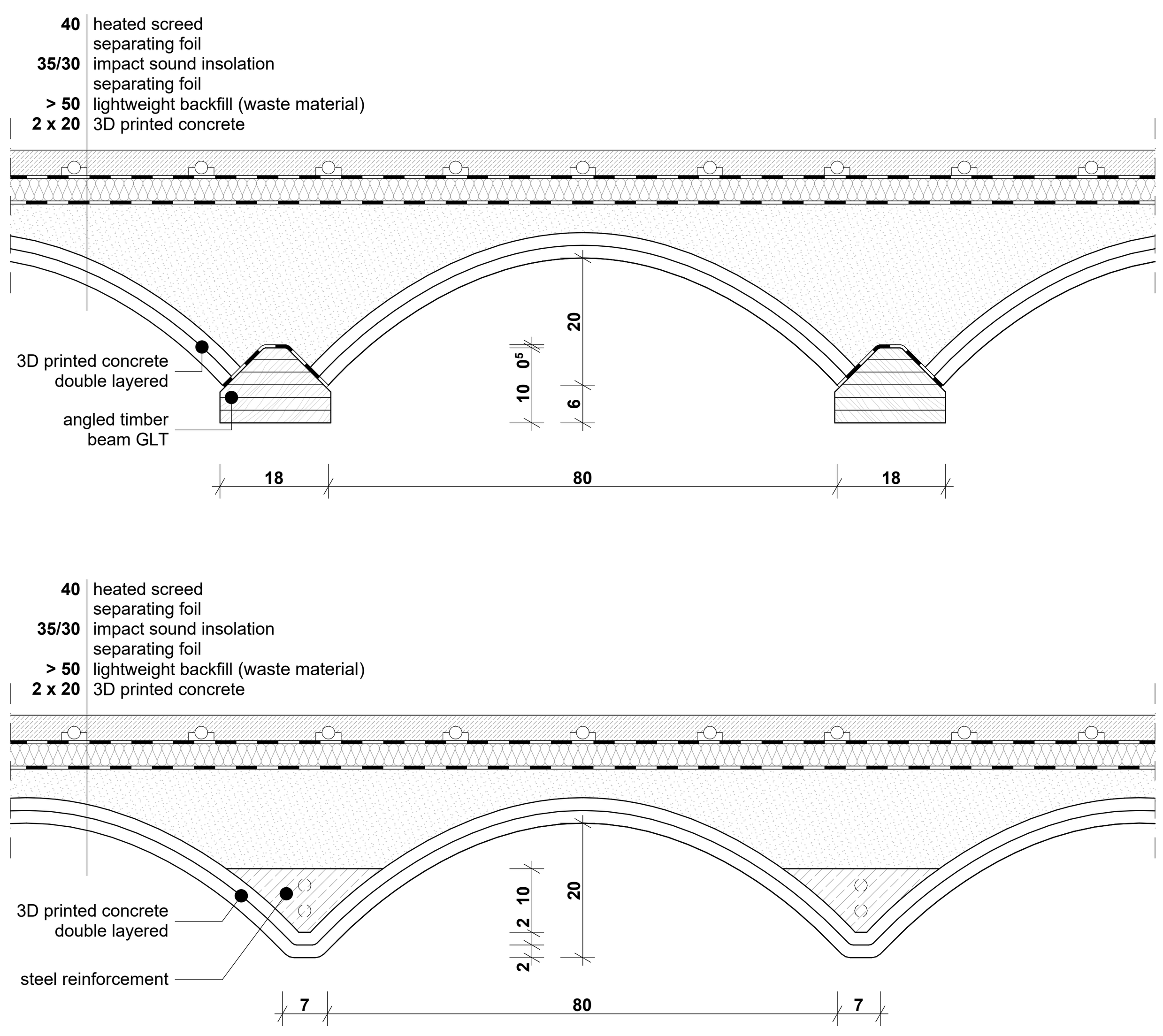

Figure 5.1: Construction details of the Kappendecke 2.0 - Top: Trapezoidal GLT beams
Bottom: Reinforced concrete backfill

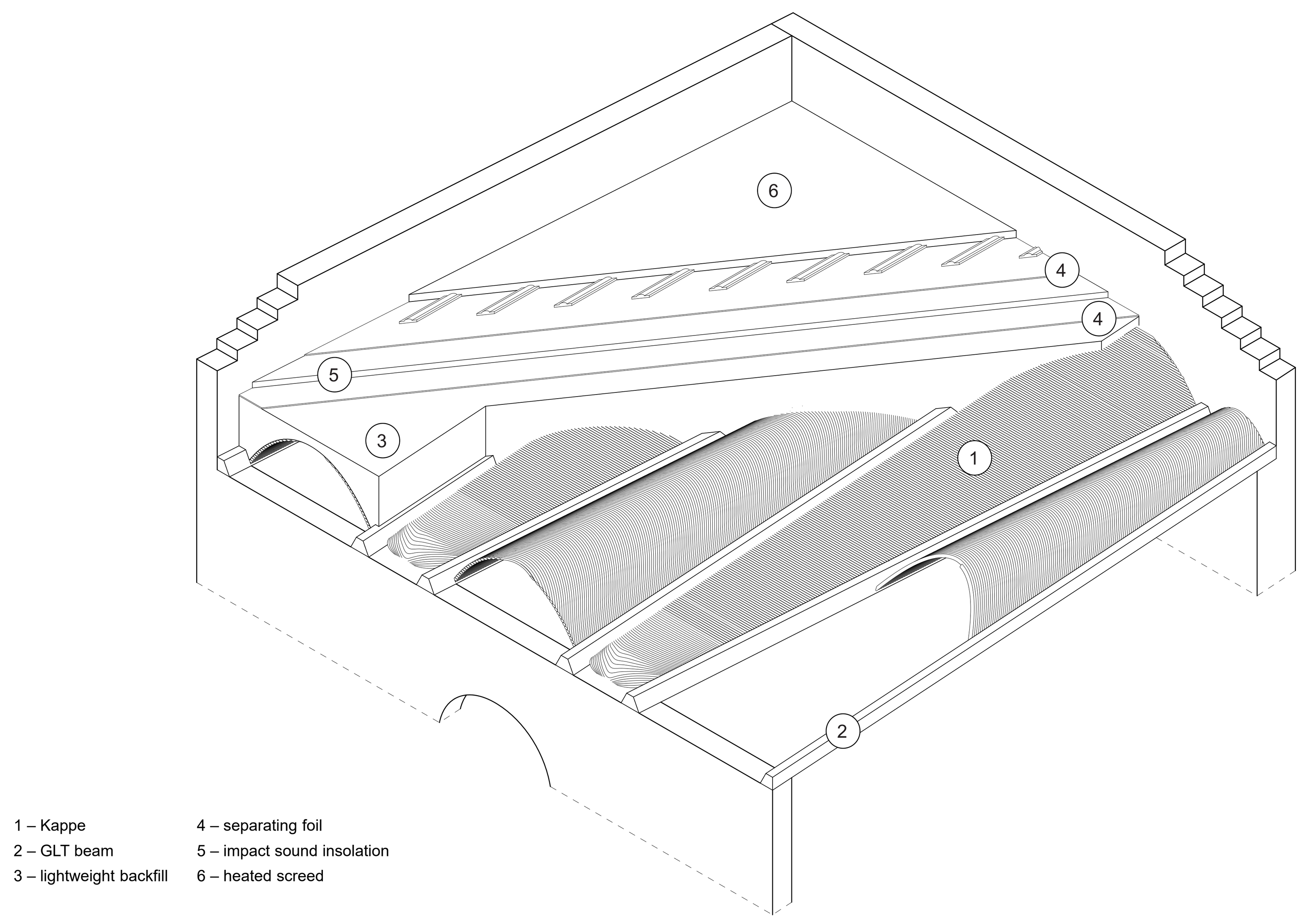

Figure 5.2: Construction system and building sequence of the Kappendecke 2.0

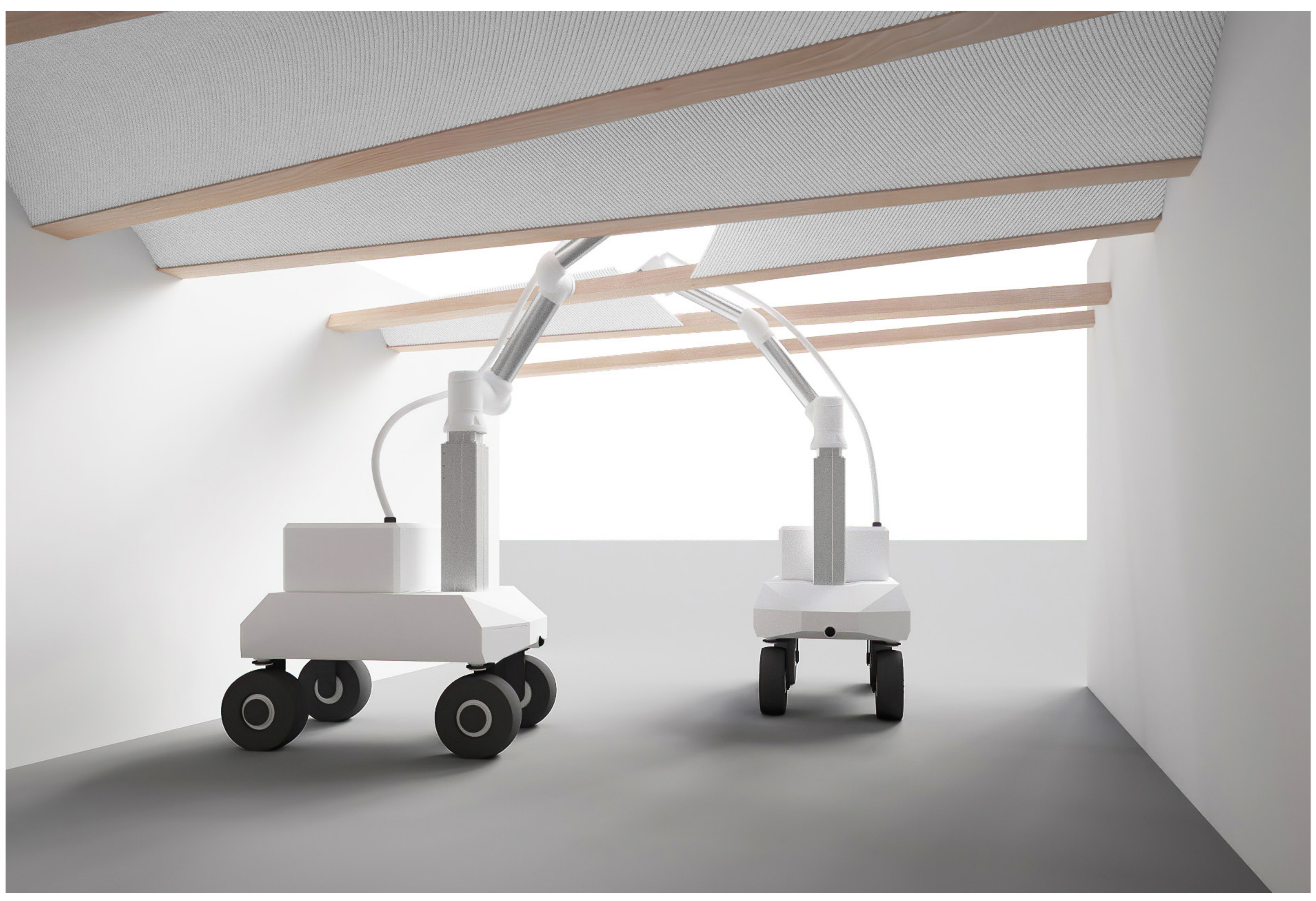

Figure 6.1: Outlook of a potential future fabrication method with multiple mobile robots - Bottom view

Figure 6.2: Outlook of a potential future fabrication method with multiple mobile robots - Top view